The One Higgs and its Connections

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I propose the notion that there is only one Higgs doublet which is responsible for electroweak symmetry breaking and all other possible scalars in any extension of the standard model are prevented from mixing with it because of a symmetry which stabilizes dark matter. This leads naturally to radiative (scotogenic) neutrino mass as well as radiative quark and lepton masses if flavor symmetry is also considered.

I.   ONE HIGGS DOES ALL?

With the discovery of the 125 GeV particle [1, 2] at CERN in 2012, and the absence of any other evidence of new physics, together with subsequent data confirming that it is indeed consistent with being the one predicted Higgs boson of the Standard Model (SM), it has become essential to ask the question: Is that it?

After all, the SM needs just the one Higgs. It is capable of doing it all, i.e. gives masses to the $W^\pm$ and Z bosons, as well as all the quarks and leptons. This means that the SM is potentially complete, and there is nothing else fundamental to discover, excepting of course the origins of neutrino mass and dark matter (DM).

On the other hand, the discovered 125 GeV particle may not be exactly the one Higgs predicted by the SM. It may still hold some surprises as its properties are being scrutinized experimentally. On the phenomenological side, it opens up the new possibility to use it as a probe of new physics, which is the topic of this workshop. On the theoretical side, we may want to understand how this one Higgs occurs in a natural extension of the SM.

II.   MORE HIGGS OR ONE HIGGS DOES MORE?

Numerous studies have been made on the extensions of the scalar sector of the SM: PACS category 12.60.Fr. In particular, two Higgs doublet models abound: Type I, II, X, Y, etc. In all such cases, the linear combination with $\langle \phi^0 \rangle = 174$ GeV, i.e. that of the SM, is in general not automatically a mass eigenstate.
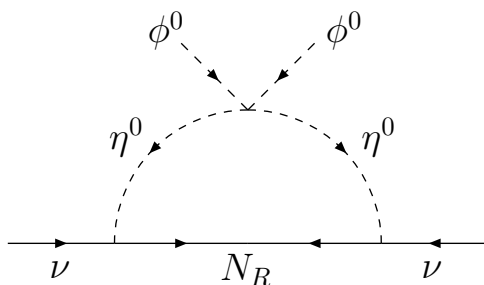
Another often studied scenario is that of flavor symmetry. To realize such a symmetry in a renormalizable theory, the Higgs Yukawa couplings $f_{ijk}\bar{Q}_{iL}d_{jR}\Phi_k$, etc. require that there be more than one Higgs doublet. What if there is only One Higgs?, i.e. a scalar doublet with $\langle \phi^0 \rangle = 174$ GeV, which is prevented from mixing with any other scalar by an approximate or exactly conserved symmetry.

The former may be realized in a model of of flavor [3] for example. Here under the symmetry $S_3 \times Z_2$, there are three Higgs doublets: $(\Phi_1, \Phi_2) \sim (2, +)$ and $\Phi_3 \sim (1, -)$. The $S_3 \times Z_2$ symmetry breaks softly to $Z_2 \times Z_2$, both of which are then also softly broken. The $(-, +)$ Higgs mediates $B - \bar{B}$ mixing with a mass ~ 1 TeV. The $(+, -)$ Higgs mediates $K - \bar{K}$ mixing with a mass ~ 10 TeV. The $(+, +)$ Higgs is almost exactly that of the SM. There is a unique prediction of this model, i.e. the branching fraction of $B_s \to \tau^+\mu^-$ may be as high as 10^{-7}, whereas that of $B \to \mu^+\tau^-$ is much more suppressed. Note that $B_s \to \mu^+\mu^-$ has been seen [4] with a branching fraction of $2.8 \ (+0.7/-0.6) \times 10^{-9}$.

The latter was the inspiration of the scotogenic model [5] of radiative neutrino mass (from the Greek *scotos* meaning darkness, which identifies this symmetry as Z_2 for dark matter. A second scalar doublet (η^+, η^0) and three neutral fermion singlets $N_{1,2,3}$ are added to the SM which are odd under Z_2, whereas all other (i.e. SM) particles are even. The complex scalar $\eta^0 = (\eta_R + i\eta_I)/\sqrt{2}$ is split so that $m_R \neq m_I$. Let $m_R < m_I$, then η_R is a dark-matter candidate. Alternatively, it may be the lightest N. Using $f(x) = -\ln x/(1-x)$, the Majorana neutrino mass matrix is given by
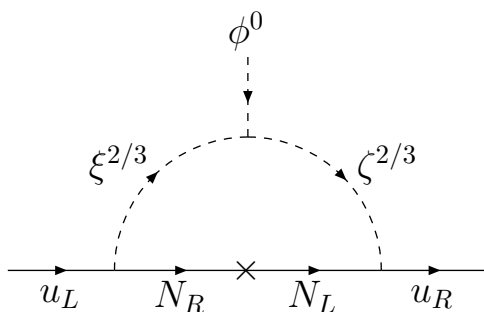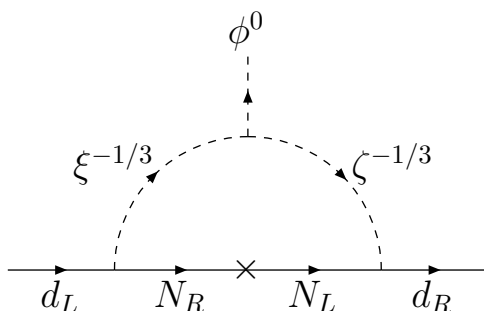
$$(\mathcal{M}_\nu)_{\alpha\beta} = \sum_i \frac{h_{\alpha i}h_{\beta i}M_i}{16\pi^2}[f(M_i^2/m_R^2) - f(M_i^2/m_I^2)].   \tag{1}$$

Dark matter is either WIMP (Weakly Interacting Massive Particle) in a freeze-out scenario, or FIMP (Feebly Interacting Massive Particle) in a freeze-in scenario.
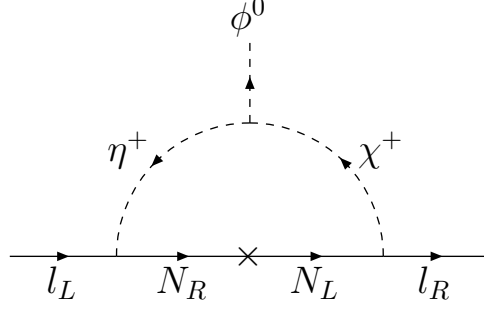
FIG. 1: One-loop generation of neutrino mass with Z_2 symmetry.

III.   THE DARK MATTER AND FLAVOR CONNECTION

The Higgs connection to W, Z bosons is fundamental to the SM and should not be changed. *Question*: What about its other connections? It has already been conjectured that it connects to neutrinos only through DM. Why not to (some) quarks and leptons? This is the subject of my recent paper [6]: Instead of the Higgs boson coupling directly to fermions, a dark $U(1)_D$ symmetry as well as a flavor symmetry (such as A_4) are imposed to forbid certain Yukawa couplings. The flavor symmetry is then softly broken and the fermion gets a radiative scotogenic mass in one loop. The $U(1)_D$ symmetry may also be broken into a residual Z_2 symmetry. Examples are shown below.   In these diagrams, there appear the analogs of scalar leptons and quarks as in supersymmetry,

FIG. 2: One-loop generation of u quark mass with $U(1)_D$ symmetry.

FIG. 3: One-loop generation of d quark mass with $U(1)_D$ symmetry.

but the model is not supersymmetric. Note that $(\xi^{2/3}, \xi^{-1/3})$ is a scalar electroweak doublet, whereas $\zeta^{2/3}$ and $\zeta^{-1/3}$ are singlets. There is also only one copy of these scalars, instead of three copies in supersymmetry because there are three families of quarks. The flavor information is carried by the $N_{1,2,3}$ singlet fermions. The $3 \times 3\ \mathcal{M}_N$ mass matrix softly breaks A_4 and its structure is transmitted to the quark and lepton mass matrices through their different couplings to the dark sector. In this way, a unified understanding of quark and lepton mixing is obtained by tracing its origin to the structure of dark matter.
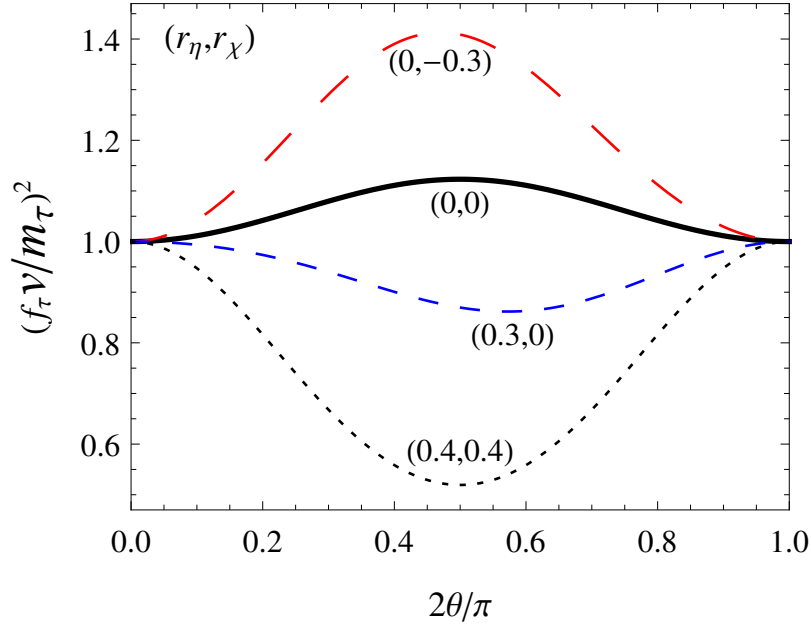
FIG. 4: One-loop generation of charged-lepton mass with $U(1)_D$ symmetry.

IV. ANOMALOUS HIGGS YUKAWA COUPLINGS

An immediate consequence of this scenario is a possible observable deviation [7] of the Higgs Yukawa coupling of $h\bar\psi\psi$ which is well-known to be given by m_ψ/v in the SM where $v = 246$ GeV. In the radiative mechanism for leptons, the doublet (η^+, η^0) and singlet χ^+ mix through the term $\mu(\eta^+\phi^0 - \eta^0\phi^+)\chi^-$, where $\langle\phi^0\rangle = v/\sqrt{2}$. Let the mass eigenstates be $\zeta_1 = \eta\cos\theta + \chi\sin\theta$, and $\zeta_2 = \chi\cos\theta - \eta\sin\theta$ with masses m_1 and m_2, then $\mu v/\sqrt{2} = \sin\theta\cos\theta(m_1^2 - m_2^2)$. Let $x_{1,2} = m_{1,2}^2/m_N^2$, the one-loop mass is

$$m_l = \frac{f_\eta f_\chi \sin\theta\cos\theta\, m_N}{16\pi^2}\left(\frac{x_1\ln x_1}{x_1 - 1} - \frac{x_2\ln x_2}{x_2 - 1}\right). \tag{2}$$

The Yukawa coupling of h to $\bar{l}l$ is now not exactly equal to m_l/v. It has three contributions, through $\eta^+\eta^-$,

FIG. 5: The ratio $(f_\tau v/m_\tau)^2$ plotted against θ for $x_1 = 3$ and $x_2 = 1$ with various (r_η, r_χ).

$\chi^+\chi^-$, and $\eta^\pm\chi^\mp$. Let $r_{\eta,\chi} = \lambda_{\eta,\chi}(m_N/\mu)^2$, then

$$\frac{f_l v}{m_l} = 1 + \frac{1}{2}(\sin 2\theta)^2(a_+ F_+ + a_- F_-), \tag{3}$$

where

$$a_+ = 1 + (x_1 - x_2)\cos 2\theta(r_\eta - r_\chi), \qquad a_- = (x_1 - x_2)(r_\eta + r_\chi), \tag{4}$$

$$F_+ = [F(x_1, x_1) + F(x_2, x_2)]/2F(x_1, x_2) - 1, \qquad F_- = [F(x_1, x_1) - F(x_2, x_2)]/2F(x_1, x_2), \tag{5}$$

with

$$F(x_1, x_2) = \frac{1}{x_1 - x_2} \left(\frac{x_1 \ln x_1}{x_1 - 1} - \frac{x_2 \ln x_2}{x_2 - 1} \right). \tag{6}$$

Note that the deviation from 1 is not suppressed by the usual loop factor of $16\pi^2$ as in other radiative-correction calculations. Take for example $x_1 = 3$ and $x_2 = 1$, then $F(3,1) = 0.324$. For m_τ, this yields $f_\eta f_\chi / 4\pi =$
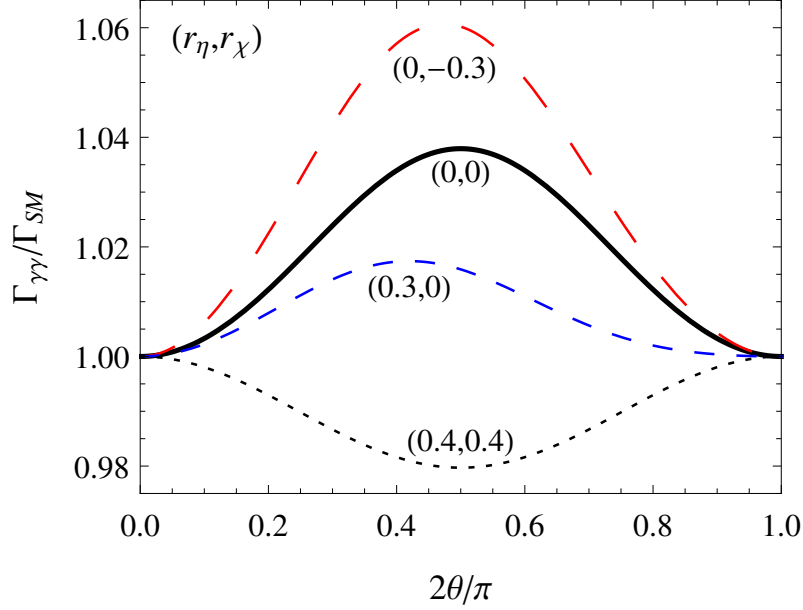

FIG. 6: The ratio $\Gamma_{\gamma\gamma}/\Gamma_{SM}$ plotted against θ for $x_1 = 3$ and $x_2 = 1$ with various (r_η, r_χ) and $\mu/m_N = 1$.

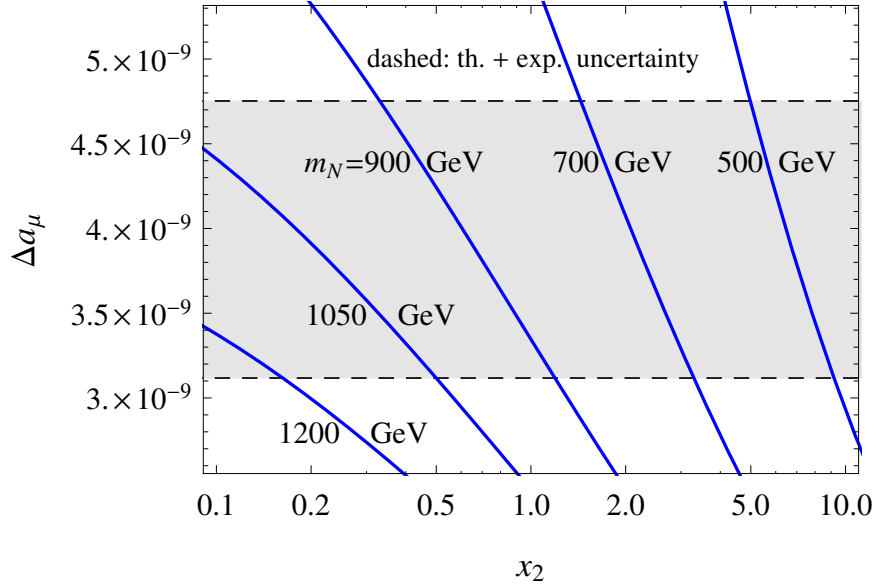FIG. 7: Δa_μ plotted against x_2 with $x_1 = x_2 + 2$ for various m_N.

$0.4(m_N/\mu)$ and $\sin 2\theta = \mu v/\sqrt{2} m_N^2$. Hence $m_N > 174$ GeV for $m_N/\mu < 1$. The effect on $(f_\tau v/m_\tau)^2$ is plotted for various values of (r_η, r_χ) in Fig. 5. The charged scalars $\zeta_{1,2}$ also contribute to $h \to \gamma\gamma$. Assuming again

$x_1 = 3$ and $x_2 = 1$, and also $\mu/m_N = 1$, $\Gamma_{\gamma\gamma}/\Gamma_{SM}$ is plotted against θ in Fig. 6. If we apply the same procedure to the muon, then

$$\Delta a_\mu = \frac{(g-2)_\mu}{2} = \frac{m_\mu^2}{m_N^2}\left[\frac{G(x_1) - G_(x_2)}{H(x_1) - H(x_2)}\right], \tag{7}$$

where

$$G(x) = \frac{2x\ln x}{(x-1)^3} - \frac{x+1}{(x-1)^2}, \quad H(x) = \frac{x\ln x}{x-1}. \tag{8}$$

This is plotted against x_2 with $x_1 = x_2 + 2$ for various m_N in Fig. 7. Note that the usual factor of $16\pi^2$ is missing in the denominator, thus allowing for a larger value of m_N to explain the experimental deviation of Δa_μ from the SM prediction.

V.   COLLIDER SIGNATURES

The dark-matter singlet neutral fermions $N_{1,2,3}$ carry flavor and their mixing pattern gets transmitted to the quarks, leptons, and neutrinos. Since flavor is organized through them, the production of scalar quarks, then $\tilde{q} \to q_{1,2}N_{1,2}$ with $N_2 \to \eta/\chi + \mu^\pm$ and $\eta/\chi \to N_1 e^\mp$ will result in

$$2 \text{ jets} + \mu^\pm + e^\mp + \text{missing energy}$$

at the Large Hadron Collider (LHC). In contrast, in the Minimal Supersymmetric Standard Model, the neutral gauginos do not carry flavor, so the decay of squarks to dark matter will mostly result in 2 jets $+ \mu^+\mu^-$ (or e^+e^-) + missing energy instead. Consider the expected 13 TeV run at the LHC. This signature is observable [8] with $S/N > 5$ where the SM background is mainly $t\bar{t}$ production. Applying the cuts: $|\eta_j| < 3$, $|\eta_e| < 2.4$, and
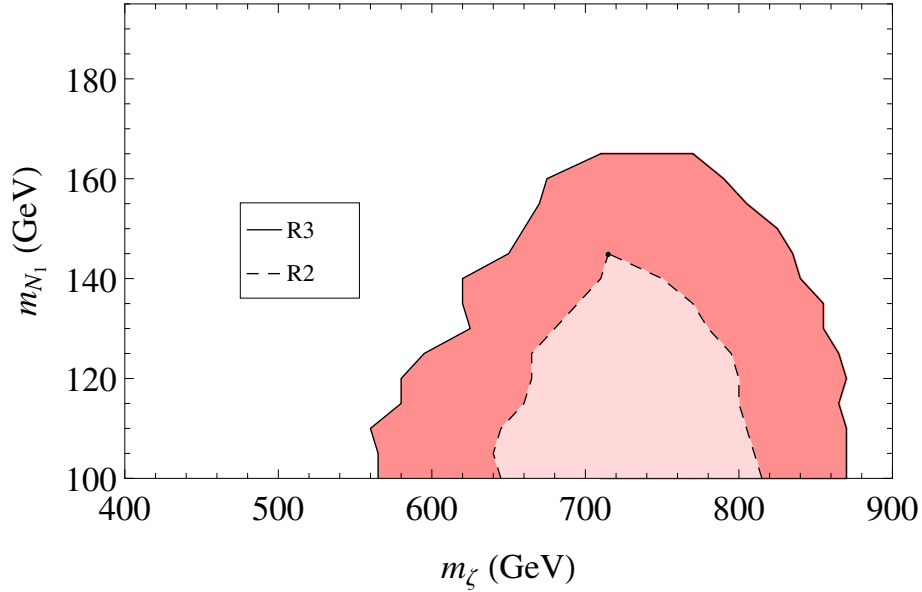

FIG. 8: Masses for N_1 and ζ that could produce a signal-to-background ratio, when compared to $t\bar{t}$ decays, larger than 5 in the opposite-sign opposite-flavor dilepton + 2 jets + missing energy signature, under the R2 and R3 cuts.

$|\eta_\mu| < 2.5$, we consider four cut regions with $m_{N_2} = 400$ GeV and $m_\chi = 200$ GeV:

$$R2 \; : \; T_T^m > 200 \text{ GeV}, \quad H_T > 600 \text{ GeV}, \quad p_T^j > 30 \text{ GeV}, \quad p_T^l > 20 \text{ GeV}; \tag{9}$$

$$R3 \; : \; T_T^m > 275 \text{ GeV}, \quad H_T > 600 \text{ GeV}, \quad p_T^j > 30 \text{ GeV}, \quad p_T^l > 20 \text{ GeV}; \tag{10}$$

$$R5 \; : \; T_T^m > 200 \text{ GeV}, \quad H_T > 350 \text{ GeV}, \quad p_T^j > 30 \text{ GeV}, \quad p_T^l > 20 \text{ GeV}; \tag{11}$$

$$R6 \; : \; T_T^m > 200 \text{ GeV}, \quad H_T > 350 \text{ GeV}, \quad p_T^j > 150 \text{ GeV}, \quad p_T^l > 25 \text{ GeV}. \tag{12}$$

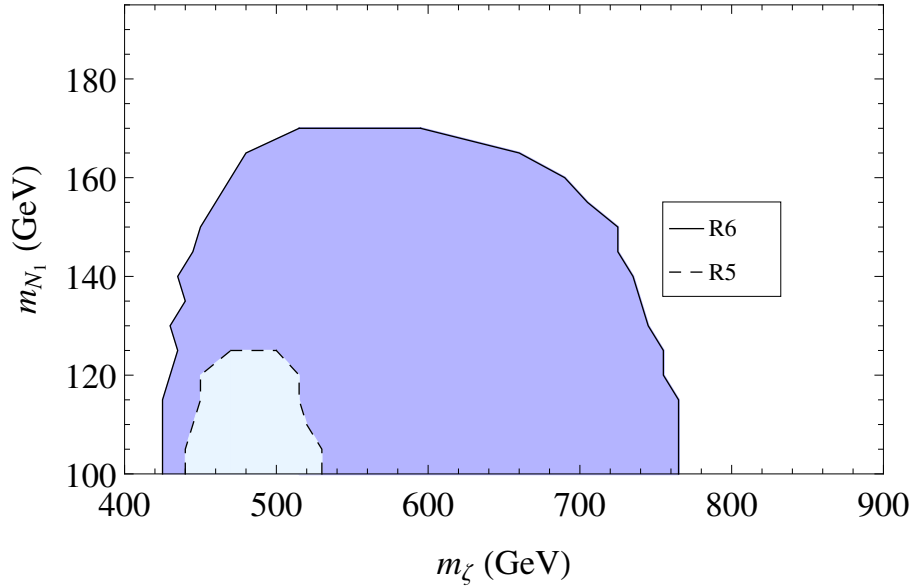The discovery domains in m_{N_1} versus m_ζ are shown in Figs. 8 and 9.

FIG. 9: Masses for N_1 and ζ that could produce a signal-to-background ratio, when compared to $t\bar{t}$ decays, larger than 5 in the opposite-sign opposite-flavor dilepton + 2 jets + missing energy signature, under the R5 and R6 cuts.

VI.   CONCLUSION

Question What does the one Higgs really tell us? The answer may be that flavor and dark matter are also connected and they do so through the one Higgs. This new notion extends the scotogenic neutrino mass to all (or most) quark and lepton masses, with flavored dark matter. In this framework, the new physics scales responsible for DM and neutrino mass are the same, say 1 TeV. If so, its impact is verifiable in the near future at the LHC.

Acknowledgments

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